Implications of long-term climate change for the Leeuwin Current

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Abstract

The Leeuwin Current is an anomalous, poleward flowing, eastern boundary current, which brings water (and associated marine biota) of warm tropical origin to the temperate south-west and the Great Australian Bight. The Current is driven by an alongshore steric height gradient which is due to the inter-connection between the Indian and Pacific oceans through the Indonesian Archipelago and the density structure of the Indian Ocean.

The Current flows all year round but exhibits a strong seasonality with the stronger flows occurring during the winter months (May - July) and is weaker during the summer (December to January). This is reflected in the coastal sealevels off Western Australia which may be used as an indication of the strength of the current. During ENSO events, the Current is also weaker due to changes in the equatorial Pacific Ocean.

Under an 'Enhanced Greenhouse' warming scenario, there is potential for the driving force of the Leeuwin Current, and its consequent influence on the biota of coastal waters, to be changed. This paper reviews the driving mechanisms of the Current and its annual and inter-annual variability. Selected scenarios under an enhanced greenhouse warming are examined to determine their impact on the strength and location of the Leeuwin Current. It is shown that, although there is a degree of uncertainty on the likely manifestations of the enhanced greenhouse effect, various scenarios indicate a possible decrease in the alongshore steric height gradient resulting in a weaker Leeuwin Current. An increase in the northward wind stress during the summer months is also predicted which could lead to a weaker Current during the summer months than present and more frequent upwelling along the West Australian coast.

Introduction

Increased emissions of carbon dioxide, methane, chlorofluorocarbons (CFC's) and nitrous oxide from human activity have resulted in additional warming of the Earth's surface. This is termed the 'Enhanced Greenhouse Effect' (IPCC 1990). The global mean air temperature is predicted to rise at a rate of 0.3°C per decade (with an uncertainty range of of 0.2°C to 0.5°C per decade) over the next century. Associated with this warming is a re-distribution of heat resulting in changes to the global climate system. This, in turn, will alter the global precipitation patterns, weather systems, frequency of climate extremes and also produce a rise in the mean sealevel (IPCC 1990). The ocean circulation is driven mainly by the global heat budget and, hence, it is envisaged that changes to the global ocean circulation may result from the enhanced greenhouse effect. This paper examines the possible effect of climate change on the strength and location of the Leeuwin Current off Western Australia.

The Leeuwin Current, a poleward eastern boundary current off the West Australian (WA) coast, is a shallow (< 300 m) narrow band (< 100 km wide) of relatively warm, lower salinity water of tropical origin that flows southward, mainly above the continental slope from Exmouth to Cape Leeuwin (Cresswell & Golding 1980, Pearce & Cresswell 1985, Church *et al.* 1989, Cresswell 1991). At Cape Leeuwin it pivots eastward, spreads onto the continental shelf and flows towards the Great Australian Bight. Satellite imagery has shown that the Current is a complex of meanders, jet-like streams and eddies, and the structure and behaviour of the Current vary monthly (Legeckis & Cresswell 1981, Pearce 1985, Prata & Wells 1990, Pattiaratchi *et al.* 1990). The Current is an important feature locally as it influences the climate of Western Australia (Gentilli 1991) and the local fishing industry (Pearce & Phillips 1988, Stequert & Marsoc 1989, Lenanton *et al.* 1991).

Similar to the other southern hemisphere ocean basins, the Indian Ocean accommodates a general anti-clockwise gyre which includes the westward flowing

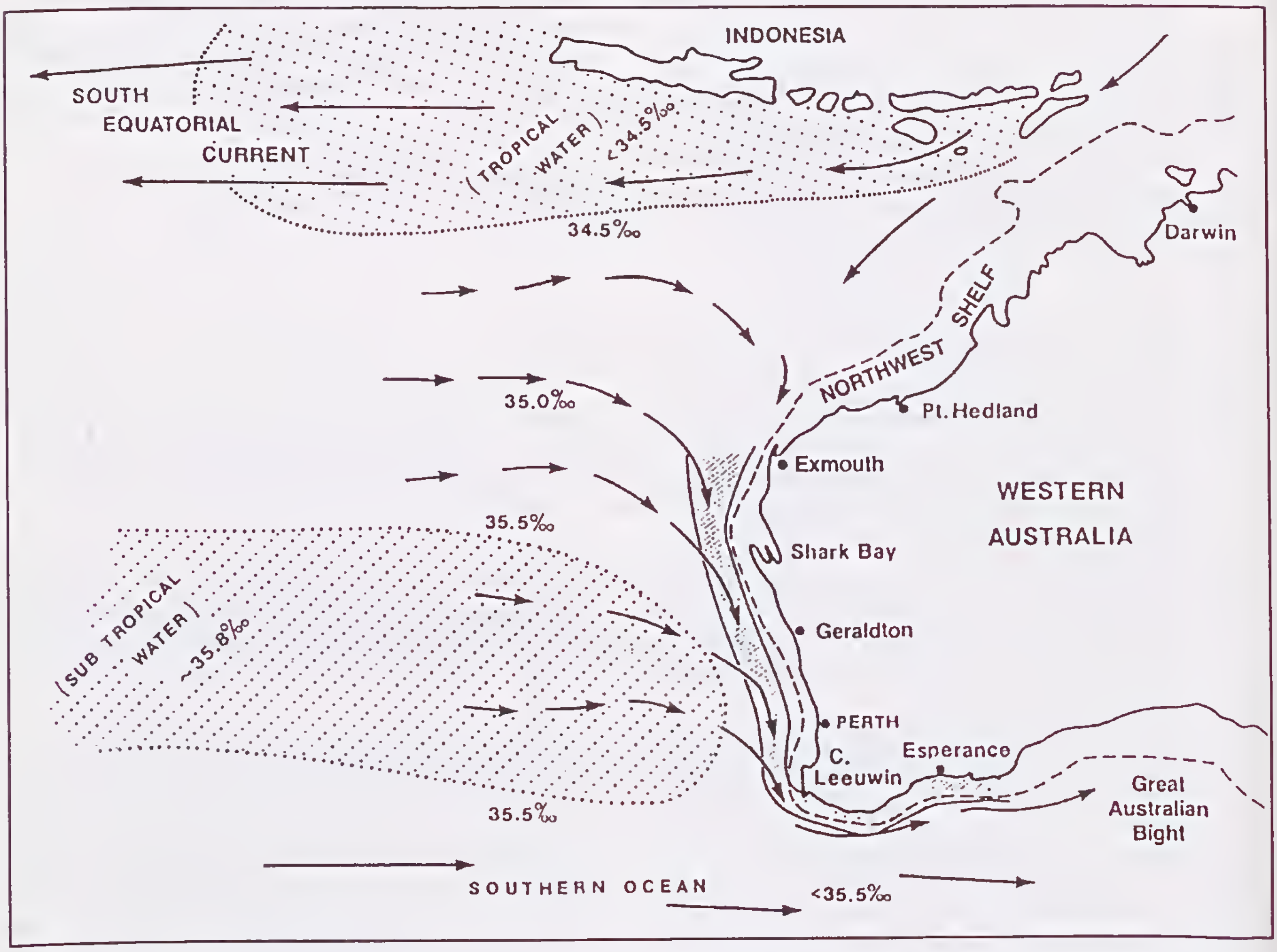

Figure 1 Schematic chart of the large-scale circulation in the eastern Indian Ocean. The Leeuwin Current is shown as the hatched area off Western Australia (From Pearce & Cresswell 1985).

South Equatorial Current from 5°S to 15°S latitude, the strong southward flowing Agulhas Current off the east coast of Africa and the eastward flowing West Wind Drift south of 40°S latitude. Traditional models of ocean circulation postulate a broad, northward return flow off the WA coast, termed the West Australian Current (see for example Tchernia 1980). However, although a net northward flow of water must exist to maintain continuity of the water circulation, field studies undertaken during the 60's and 70's failed to provide any evidence for this equatorward flow. With the advent of satellite tracked drogues and infra-red satellite imagery, the poleward flowing Leeuwin Current was identified (Cresswell 1991). It is now known that the West Australian Current is located seaward of the Leeuwin Current and may extend over more than half of the Indian Ocean as a very slow return flow towards the equator (Thompson & Veronis 1983).

A unique feature of the Indian Ocean circulation is the inflow from the Pacific Ocean through the Indonesian Archipelago. With the exception of the common inter-connection between all the oceans with the Southern Ocean, this is the only connection between any two ocean basins and is an important factor in the generation of the Leeuwin Current.

This paper investigates the possible effect of long-term climate change on the strength and location of the Leeuwin Current by reviewing the proposed generating mechanisms of the Current and the observed variability on seasonal and inter-annual time scales. Various greenhouse scenarios (see for example, IPCC 1990) are examined to identify predictions which may alter the driving forces of the Current. Assuming that any change to the generating forces, as a result of climate change, will influence the strength and location of the Current, predictions are made on the likely behaviour of the Leeuwin Current under an enhanced greenhouse scenario.

Generating mechanisms

Mechanisms for the generation of the Leeuwin Current have been studied by several investigators (Church *et al.* 1989, Godfrey & Ridgway 1985, Pearce & Cresswell 1985, Thompson 1984, 1987, Weaver & Middleton 1989, Batteen & Rutherford 1990, Godfrey & Weaver 1991). There is general consensus that the driving force of the Leeuwin current is an alongshore steric height gradient which overwhelms the opposing equatorward wind stress. The source of the Leeuwin Current water is from the Indian Ocean from the west and a component (which originates from the Pacific Ocean) from the North West continental shelf. The South East Trade Winds, in the Pacific Ocean, drive the South Equatorial Current westwards advecting warm surface waters towards Indonesia. This results in the flow of warm, low-salinity water from the western Pacific Ocean through the Indonesian Archipelago into tropical regions of the Indian Ocean. This, together with geostrophic inflow of water from the Indian Ocean, results in the sealevel in the tropics being some 55 cm higher than that along the southern coast of Australia (Pearce & Cresswell 1985). The formation and location of the Leeuwin Current are illustrated schematically in Fig. 1.

The meridional gradient of steric height induces a weak geostrophic eastward flow of central Indian Ocean subtropical water toward the coast, between latitudes of 15°S and 35°S. The easterly flow of subtropical water is deflected southward along the edge of the West Australian continental shelf. In the north, the inflow is augmented by tropical water from the North West Shelf. Further south, the continuous inflow from the west accelerates the flow towards Cape Leeuwin, before it turns eastward into the Great Australian Bight. The relative contributions of North West Shelf and central Indian Ocean water, and the mechanism for sustaining the strong meridional steric height gradient, are still under investigation.

Initial investigations (Godfrey & Golding 1981) suggested that the Pacific-Indian Ocean throughflow may be sufficient to sustain the Leeuwin Current. More recent modelling studies (Godfrey & Weaver 1991, Weaver & Middleton 1989) indicate that the Leeuwin Current is largely unaffected by the throughflow magnitude (though the density profile water in the Indonesian region is important, since it controls the longshore pressure gradient along the Leeuwin Current). McCreary *et al.* (1986) suggest that vertical mixing is necessary to support the steric height gradient. The modelling work of Batteen & Rutherford (1990) confirms that the Leeuwin Current can be maintained by the mean thermal structure of the Indian Ocean, but it may be enhanced by the addition of warmer North West Shelf waters. Godfrey & Weaver (1991), using climatological data from Levitus (1982), argue that the propagation of internal Kelvin waves through the Indonesian Archipelago and subsequent western propagation of internal Rossby waves, allows for approximate equilibrium of the specific volume anomaly (SVA) profiles (in the upper few hundred metres) on the North West Shelf, with those in the western equatorial Pacific. The resulting relatively warm pool of surface water, means that surface temperatures are above global equilibrium temperatures (Haney 1971) for west coast water south of 15°S latitude. Consequently, the water of the Leeuwin Current may be expected to lose heat to the atmosphere, resulting in convective overturn and the formation of deep mixing layers. This is confirmed by the observations of Hamilton (1986). There now seems to be general acceptance of the importance of this surface cooling in maintaining the strength of the meridional steric height gradient.

Observed variability

Seasonal changes

In order to examine the fluctuations in the strength of the Leeuwin Current over seasonal and inter-annual time scales, some measure of the intensity of the Current over the complete geographic area of influence is required. In the absence of continuous field measurements of currents, some other measurement related to the Leeuwin Current must be used. Using sea surface temperature (SST) distributions derived from satellite imagery, Prata *et al.* (1989) have defined a 'Leeuwin Current Index (LCI)'. However, the availability of satellite derived SST distributions is limited (approx. 10 years of data) and hence cannot be used to examine long-term changes. Many investigators (see for example, Sturges 1974, Reed & Schumacher 1981, Pearce & Phillips 1988) have shown that changes in mean sealevel monitored at tide gauges may be used to derive oceanographic information such as variations in flow and/or changes in thermohaline properties. For the Leeuwin Current, Pearce & Phillips (1988) have assumed that changes in the strength of the Current are reflected in mean sealevel changes which have an annual mean amplitude of 20 cm (Fig. 2). During October to March the Leeuwin Current is weaker as it flows against the maximum southerly winds, whereas between April and August the Current is stronger as the southerly winds are weaker (Godfrey & Ridgway 1985).

This is reflected in both the SST distributions derived from satellite imagery (Prata *et al.* 1989, Pearce & Prata 1990) and the mean sealevel at Fremantle (Fig. 2).

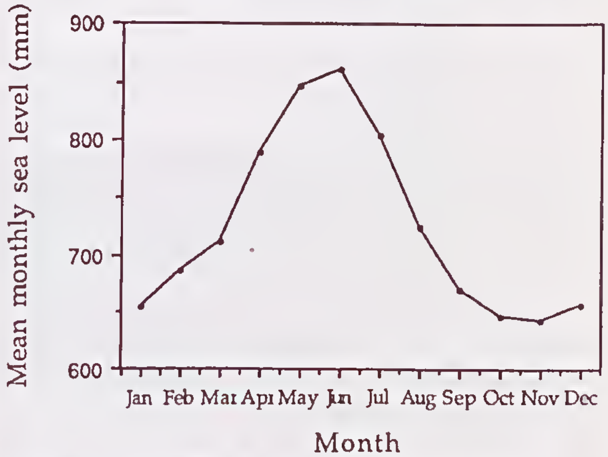

Figure 2 Monthly mean sealevel at Fremantle between 1959 & 1989 indicating that the sealevel has a seasonal amplitude of 20 cm and the maximum occurs during June (Data courtesy of the Tidal Laboratory, Flinders Institute for Atmospheric and Marine Science).

Here, the sealevel is higher between April and August when the Leeuwin Current is stronger (lower wind stress) and lower between October and January when the Current is weaker (high wind stress).

Geographical distribution of the seasonal variations in mean sealevel along the west coast of Australia indicates a progressive feature (Fig. 3 and Pariwono *et al.* 1986). On the North West Shelf, the maximum occurs during March whilst in the South West corner, the maximum occurs in May or June (Fig.s 2 and 3); this seasonal movement of the sealevel maximum reflects the southward passage of the Leeuwin Current pulse (Church *et al.* 1989).

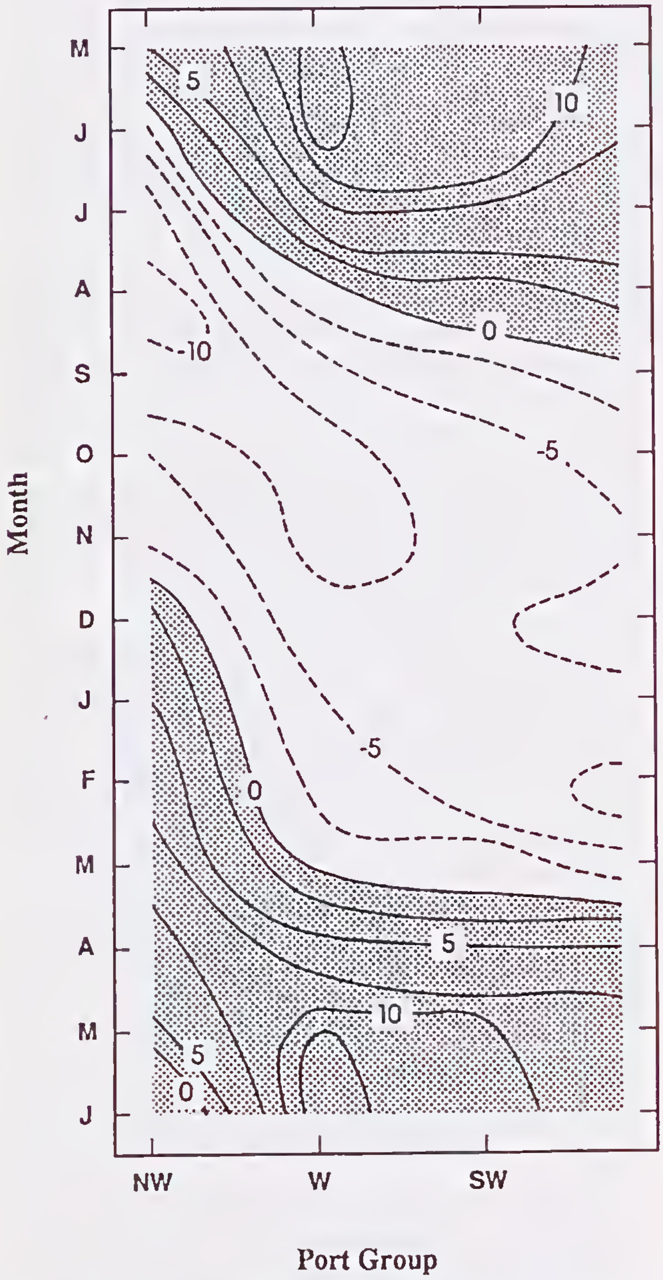

Figure 3 Geographic distribution of the seasonal variation in sealevel (cm) along the Western Australian coastline. Port Groups: NW - north-west (Darwin and Port Hedland); W - West (Geraldton, Fremantle and Bunbury); SW - south-west (Albany and Esperance). (after Pariwono *et al.* 1986).

In summary, although the Leeuwin Current flows all year round, it exhibits a strong seasonality with the stronger flows occurring during the winter months (May - July) which is reflected in the coastal mean sealevel (Fig. 2). Godfrey & Ridgway (1985) have also shown that there is a very good correlation between the coastal mean sealevel at Geraldton and the steric sealevel. Hence, the mean sealevel at Fremantle (or at any other south-west coast station) may be used as an indicator of the strength of the Current.

Inter-annual Changes

El Niño-Southern Oscillation (ENSO) events are the result of complex interactions between the ocean and the atmosphere in the tropical Pacific Ocean and have been associated with climatic and environmental anomalies around the world (Philander 1990). Two or three times each decade anomalously warm water, approximately 2-4°C above normal, appears off the coast of Peru and Ecuador and persists for a number of seasons. Normally the Peruvian coast is a region of strong coastal upwelling (Pearce 1991). During ENSO events, however, warm equatorial water from the western Pacific Ocean is transported eastward and flows southwards along the Peruvian coast to replace the cold, nutrient-enriched waters. It is now known (Philander 1990) that during an ENSO event, there is high surface pressure over the western and low sea surface pressure over the south-eastern tropical Pacific Ocean. This coincides with heavy rainfall, unusually warm surface waters and relaxed Trade Winds in the central and eastern tropical Pacific (Philander 1990).

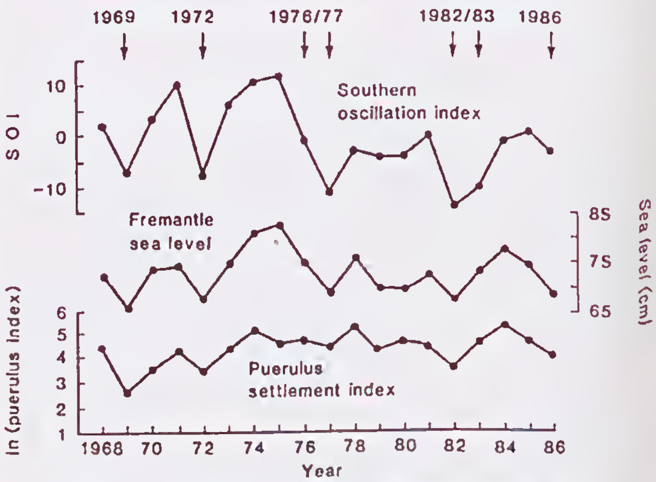

Figure 4 Time series of the annual Southern Oscillation Index (the normalised difference in surface atmospheric pressure between Darwin and Tahiti, a measure of the potential ENSO events), west coast sealevel (a measure of the strength of the Leeuwin Current) and the Puerulus Settlement Index (a measure of rock lobster recruitment) along the West Australian coast (from Pearce & Phillips 1988). The arrows indicate ENSO events.

Pearce & Phillips (1988) have demonstrated a strong correlation between the Southern Oscillation Index (SOI, the normalised difference in surface atmospheric pressure between Darwin and Tahiti, a measure of the potential of ENSO events), west coast sealevels (a measure of the strength of the Leeuwin Current, see above) and the Puerulus Settlement Index (a measure of recruitment to the rock lobster fishery). During normal years, the coastal annual mean sealevels are relatively high indicating that the Leeuwin Current is strong and the settlement of pueruli in coastal reefs is relatively high. During ENSO years, coastal sealevels fall and the inferred transport in the Leeuwin Current is weaker (Fig. 4). Extension of this time series to include the annual Fremantle sealevel data for the period 1897 to 1990 indicates that each ENSO event during this period (extracted from Quinn *et al.* 1987) is associated with a transient decrease in the annual mean sealevel (Fig. 5). This confirms the findings of Pearce & Phillips (1988) and Prata *et al.* (1989) that the Leeuwin Current is weaker during ENSO years.

A weaker Leeuwin Current during an ENSO event may be explained as follows: in a 'normal' situation, the South East Trade Winds in the Pacific Ocean set up high steric heights at the north end of the Australasian continent; the gradient between these high steric heights and the thermally-set low steric height off southwestern Australia drives the Leeuwin Current. During ENSO years, the Trade Winds relax and the steric height at the north end of the Australasian continent is lower. This results in a decreased alongshore pressure gradient along the West Australian coastline resulting in a weaker Leeuwin Current.

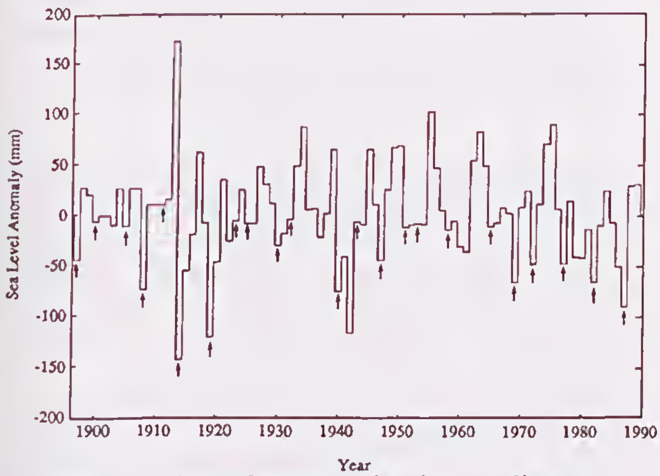

Figure 5 Annual mean sealevel anomalies at Fremantle between 1887 and 1990. The arrows indicate the occurrence of ENSO events as documented by Quinn *et al.* 1987. A decrease in the mean sealevel is seen to be associated with ENSO events (Data courtesy of the Tidal Laboratory, Flinders Institute for Atmospheric and Marine Science).

Scenarios

The dominant issue in the current discussion deals with scenarios for long-term climate change caused by the enhanced greenhouse effect due to increased concentrations of carbon dioxide, methane, CFC's and other trace gases since the industrial revolution. Various scenarios have been proposed based on general circulation model (GCM) simulations (see for example IPCC 1990, Evans 1990) and there is substantial uncertainty on the likely manifestations of the enhanced greenhouse effect. Of these, the following are of relevance in examining the potential changes to the strength and location of the Leeuwin Current.

(i) A global mean air temperature increase of approximately 1°C above the present value by 2025 and 3°C by the end of the next century will lead to a coincident increase in the sea surface temperature. This warming will not be uniform throughout the globe. It is expected that the warming of the mid-latitudes will be higher than in the equatorial regions (IPCC 1990).

(ii) GCM's have so far had limited success in simulating realistic ENSO events (McCreary & Anderson 1991). Hence, there is no clear indication as to the likely changes in the frequency of ENSO events.

(iii) The West Wind Belt (the Roaring 40's) may contract poleward by 5° to 10° latitude, therefore increasing the equator-pole pressure gradients. The Sub-tropical High Pressure Ridge should also move south and may broaden. Weaker Trade Winds are likely (Siegfried *et al.* 1990).

(iv) The mid-troposphere in the tropics will warm to a greater degree than the lower atmosphere, suppressing vertical convection and enhancing wind shear (Evans 1990).

(v) The equatorward alongshore wind stress during the summer months may increase (Bakun 1990).

The different heating rate between the tropics and mid-latitude waters (see (i) above) may result in a decrease in the alongshore steric height gradient driving the Leeuwin Current contributing to a decrease in the strength of the flow.

Weaker Trade Winds in the equatorial Pacific (see (iii) above) may result in a decrease in the strength of the South Equatorial Current (i.e. a decrease in the pooling of warmer water against the Indonesian Archipelago). In terms of the ocean circulation, this effect would be similar to that observed during ENSO events resulting in a weaker Leeuwin Current. The resultant alteration in the specific volume anomaly (SVA) profile in the surface waters would be transferred to the North West Shelf waters, and perhaps lead to a decrease in surface water cooling. This in turn may also reduce the alongshore steric height gradient, weakening the driving mechanism of the Leeuwin Current. Godfrey & Weaver (1991) have shown, from modelling studies, that if the SVA profile in the western Pacific is replaced by that in the eastern Pacific, a "Peru Current", i.e. equatorward flow together with upwelling, would be established along the West Australian coast. However, current GCM's are unable to predict the likely changes in the SVA profile in the ocean under an enhanced greenhouse scenario and, hence, it is not possible to predict whether a reduced Leeuwin Current or even a "Peru Current" would be present off Western Australia.

Although there is no clear indication as to the likely changes in the frequency of the ENSO events (see (ii) above) a long-term change in the mean value of the Southern Oscillation Index (SOI) would be important for the intensity of the Leeuwin Current. If under an enhanced greenhouse scenario the mean value of SOI increases (decreases), then the Leeuwin Current will be stronger (weaker).

The strong equatorward alongshore wind stress during the summer months is maintained by a strong atmospheric pressure gradient between a thermal low-pressure cell that develops over the heated land mass and the higher barometric pressure over the cooler ocean (Bakun 1990). It has been shown that the Leeuwin Current is weaker during the summer months as it flows against the maximum southerly wind stress (Godfrey & Ridgway 1985). Under an enhanced greenhouse scenario, the gradient between the two pressure systems over land and the ocean may be enhanced, resulting in an intensification of the equatorward wind stress (see (v) above). This would lead to further weakening of the Current during the summer months with the possibility of more frequent upwelling. Analysis of wind data from the major oceanic upwelling areas (Peru, California, Canary Current systems) have shown (Bakun 1990) that the equatorward alongshore wind stress has increased over the past 40 years leading to an intensification of the coastal upwelling systems. This result may indicate that the equatorward wind stress has already increased due to the enhanced greenhouse effect (Bakun 1990).

Implications for Biota

The presence of tropical marine organisms off the west coast of Australia and in the Great Australian Bight has been attributed to the Leeuwin Current (Maxwell & Cresswell 1981, Cresswell 1985). The Current also plays an important role in the life cycle of the southern blue fin tuna (*Thunnus maccoyii*) which has it's spawning area off the North West Shelf (Fig. 6). The larvae and young fish (< 2 years old) are carried southwards by the Leeuwin Current and are found in the Great Australian Bight and off the east coast of Australia. Papers appearing in this issue have also identified the role of the Leeuwin Current in the distribution of seagrass and algae (Walker 1991), coral spawning and distribution (Simpson 1991, Hatcher 1991), western rock lobster (Pearce & Phillips 1988), coastal scallop and fin fish stocks (Lenanton *et al.* 1991) and the sea bird distribution (Wooller *et al.* 1991). Hence, it is clear that the Current plays a major role in the biota off the west and south coasts of Australia

With regard to possible changes in the Leeuwin Current under an enhanced greenhouse scenario, those marine organisms which are dependent on higher temperatures associated with the Current may not be greatly influenced, as a slackening of the Current may be countered by a global sea surface warming. Biota which are dependent on the advective processes of the Current, such as the western rock lobster and southern blue fin tuna, may be more seriously affected. However, a weaker Leeuwin Current and an increase in the northward wind stress may also give rise to more frequent coastal upwelling (see above). This alternate nutrient enrichment may enhance the productivity associated with the continental shelf waters.

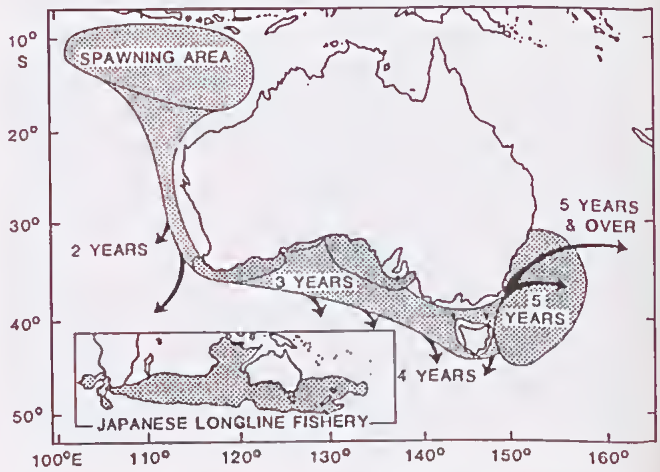

Figure 6 Spawning area and principal migration routes of the Southern blue fin tuna (*Thunnus maccoyii*). The dotted areas show the Australian fleet fishing grounds (from Stequert & Marsac 1989).

Conclusions

This paper has reviewed the proposed generating mechanisms of the Leeuwin Current and observed changes at annual and inter-annual time scales. Possible future changes to the location and strength of the Current and associated biota as a result of the enhanced greenhouse warming have been discussed. Based on these, the main conclusions are:

(a) The Leeuwin Current is driven by an alongshore steric height gradient which is generated due to the inter-connection between the Indian and Pacific Oceans through the Indonesian Archipelago (Godfrey & Ridgway 1985) and the density structure of the Indian Ocean (Batteen & Rutherford 1990).

(b) The Current flows all year round but exhibits a strong seasonality with the stronger flows occurring during the winter months as reflected in the mean sealevel at coastal stations. This annual variation in the Current is due mainly to changes to the northwards component of wind stress and also to a slight reduction in the steric height gradient. During October to March the Leeuwin Current is weakest as it flows against the strong northwards wind stress, whereas between April and August the Current is strongest as this wind stress is weaker.

(c) The mean sealevel at Fremantle (or at any other south-west coast station) may be used as an indicator of the strength of the Current.

(d) During ENSO events, the Trade Winds relax and the South Equatorial Current in the equatorial Pacific is weaker with a corresponding decrease in the alongshore pressure gradient resulting in a weaker Leeuwin Current.

(e) Although there is great uncertainty on the likely manifestations of the enhanced greenhouse effect, various scenarios relevant to determining the strength and location of the Current indicate a possible decrease in alongshore steric height gradient which may result in a weaker Leeuwin Current.

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